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OPTICAL EFFECTS OF PIGMENTATION ON TEMPERATURE RISE IN A TWO-LAYER SKIN SIMULANT SYSTEM DURING IRRADIATION

John R. Piergallini, et al

Naval Air Development Center
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It is demonstrated that from a knowledge of the thermal and optical properties of each layer of a two-layer system, together with the amplitude and distribution of the energy input, it is possible to predict temperature rises at depth in the second layer of a two-layer system. By varying the optical properties of the first layer and observing the temperature rises at depth in the second layer, the experimental results can be used to verify mathematical expressions for optical and heat transfer processes of the two layers.

Such a system was devised to determine the thermal concuctivity between a silicone rubber patch and the living skin irradiated. It may also be used in evaluations of other two-layer systems where reflectance, transmittance and heat transfer properties are known and must be accounted for in the mathematical model.

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SUMMARY

It is demonstrated that from a knowledge of the thermal and optical properties of each layer of a two-layer system, together with the amplitude and distribution of the energy input, it is possible to predict temperature rises at depth in the second layer of a two-layer system. By varying the optical properties of the first layer and observing the temperature rises at depth in the second layer, the experimental results can be used to verify mathematical expressions for optical and heat transfer processes of the two layers.

Such a system was devised to determine the thermal conductivity of intact living skin by measuring the interface temperature between a silicone rubber patch and the living skin when irradiated. It may also be used in evaluations of other two-layer systems where reflectance, transmittance and heat transfer properties are known and must be accounted for in the mathematical model.

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ACKNOWLEDGMENT

The assistance of John A. Weaver in providing the silicone patches and their properties and the technical assistance of Lambert R. Munroe are gratefully acknowledged.

INTRODUCTION

Burn effects of exposure to non-ionizing radiation, whether of low-level or thermonuclear intensity, depend upon the optical as well as the thermal properties of skin and whatever protective cover it may have. Pigmentation of the unprotected skin may greatly influence the magnitude and depth of penetration of incident radiation depending upon its wavelength. It is therefore important to be able to measure the thermal conductivity of intact human skin and to be able to predict, from a knowledge of the optical and thermal properties of both the skin and its covering, the effect of incident radiation of known wavelength and intensity.

We propose to adapt a two-layer heat transfer system to a system for determining the thermal properties of one layer of material from a knowledge of the thermal properties of the other layer when the temperature rise on irradiation and intensity of the energy are known (1). In this way a patch of suitable material of known properties may be laid upon the living skin with interface or surface temperature rise being measured during irradiation, making it possible to calculate the thermal conductivity of living skin. The validation of the proposed system entails the use of a series of silicone rubber patches of different optical properties representing various degrees of pigmentation. The patches are combined with a skin simulant to form a two-layer system, analogous to a rubber-covered living skin combination, in which mathematical

expressions of heat transfer relationships can be verified experimentally. This paper describes the heat transfer process and may be used in general applications involving two-layer systems as well as in our specific use.

PROCEDURE AND MATERIALS

The two-layer system is irradiated by a graphite imaging furnace (2) to validate experimentally the temperature rises at depth in the second layer which are determined mathematically. Computer techniques are used to calculate the optical properties and energy distribution of the two-layer system. An equation for transient heat flow through a two-layer wall as proposed by Griffith and Horton (3) is used to determine temperature rise at depth in the second layer as it varies with time.

Each of seven silicone rubber patches designated W(white), W + 1, W + 2, W + 3, W + 4, W + 5 and Black is used as the first layer. Silicone rubber was chosen because the thermal properties are known, it can be prepared in fairly thin sheets, it does not wrinkle or swell appreciably when irradiated and it forms a tight contact with the backing material. The thickness of the patches is 0.0532 cm $\pm$ 0.0008cm. Each patch was pigmented differently to vary reflectance and transmittance properties. The backing material is the skin simulant device fabricated by the Naval Material Laboratory, N. Y. (4). Optical properties were measured with the Beckman DK-2A Spectrophotometer. Reflectance and transmittance were determined for each silicone rubber patch. Transmittance was

measured for a slice of the skin simulant 0.047 cm thick, approximating the depth of the thermocouple beneath the surface, and reflectance in the full thickness (1cm). Using computer techniques the absorptance is calculated at each wavelength for each layer:

$$A1(\lambda) = 1 - [R1(\lambda) + T1(\lambda)] \qquad \text{Eq. (1)}$$

$$A2(\lambda) = 1 - [R2(\lambda) + T2(\lambda)] \qquad \text{Eq. (2)}$$

where

1 refers to top layer, 2 refers to base layer and

$A(\lambda)$ = Absorptance at each wavelength interval, %

$R(\lambda)$ = Reflectance at each wavelength interval = $R(\lambda)SC(\lambda)$,%

$T(\lambda)$ = Transmittance at each wavelength interval, %

λ = Wavelength of radiation, microns

$SC(\lambda)$ = Setting correction at each wavelength interval (5),%

A computer program was developed to calculate: H1 which is the heat flux absorbed at the front surface of the first layer, H1B which is the heat flux absorbed at the back surface of the first layer and H2 which is the heat flux absorbed at the front surface of the second layer. Knowing the color temperature and the transmittance properties of pyrex, the equivalent black body radiation (BBR) curve is determined. The graphite imaging furnace operates at a color temperature of 1800 degrees Kelvin, the element being enclosed in an argon-filled pyrex bell jar which limits the radiation to the spectral region between 0.29 and 3.9 microns. By multiplying the hemispherical black body radiation curve taken from the International Critical Tables, Figure 1, by the transmittance curve of the pyrex

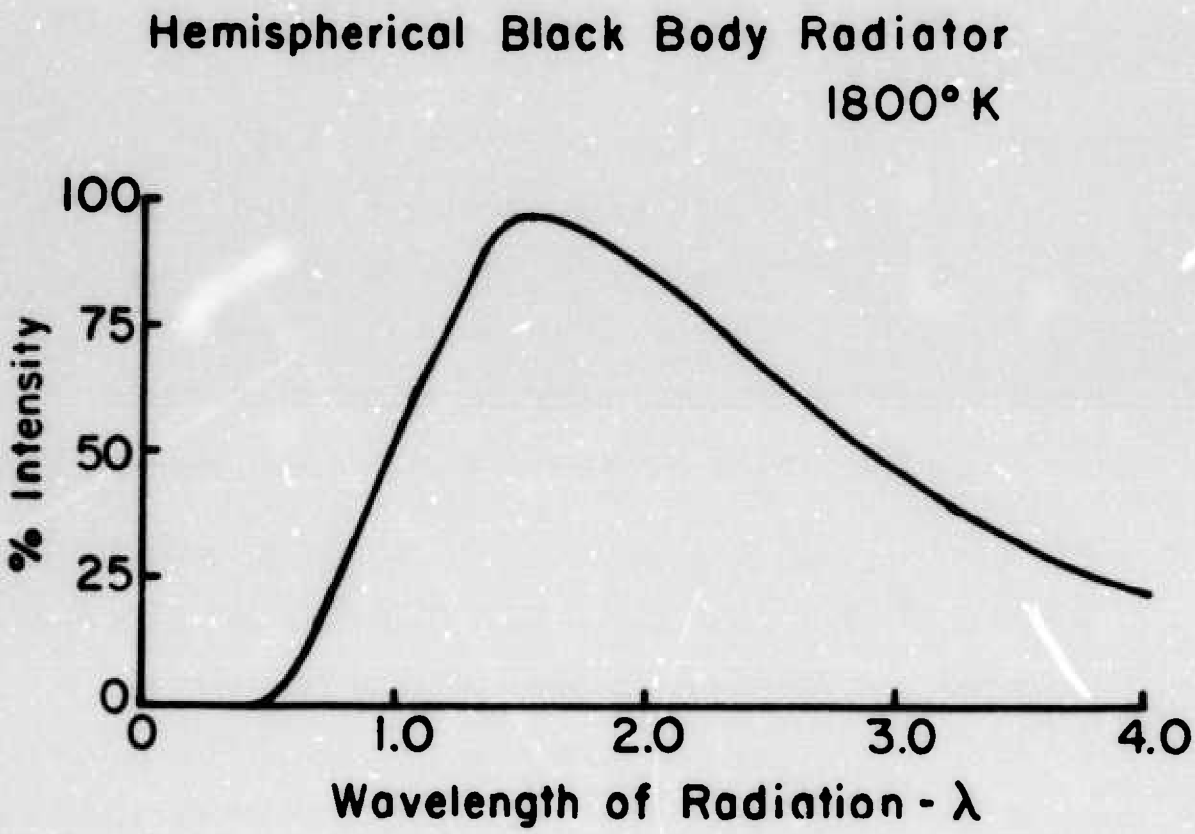


Fig. 1. Hemisherical Radiation of Black Body Radiator

bell jar, Figure 2, we can establish the black body radiation distribution of the incident energy, Figure 3. Black Body Radiation Data, Setting Correction Data, Reflectance and Transmittance Data and a copy of the computer programs and outputs can be found in Appendix A.

The energy under the BBR curve must be equal to the incident energy which is measured by a totally absorbing radiometer. This is accomplished by multiplying the incremental value of the BBR data by the incident energy of the source and dividing by the average value of the BBR data, thus the total energy, or area under the BBR curve, is equal to the energy measured by the radiometer in conformance with the BBR distribution.

The optical properties of the two-layer system are accounted for by use of the equations for determining H1, H1B and H2:

$$H1 = \frac{Q}{BBR_{(AV)}{}^{N}} \sum_{\lambda = 0.375}^{\lambda = 3.825} BBR(\lambda)A1(\lambda) \qquad \text{Eq. (3)}$$

$$H1B = \frac{Q}{BBR_{(AV)}{}^{N}} \sum_{\lambda = 0.375}^{\lambda = 3.825} BBR(\lambda)[T1(\lambda)R2(\lambda)A1(\lambda) + T1(\lambda)R2(\lambda)R1(\lambda) R2(\lambda)A1(\lambda)] \qquad \text{Eq. (4)}$$

$$H2 = \frac{Q}{BBR_{(AV)}{}^{N}} \sum_{\lambda = 0.375}^{\lambda = 3.825} BBR(\lambda)[T1(\lambda)A2(\lambda) + T1(\lambda)R2(\lambda)R1(\lambda)A2(\lambda)] \qquad \text{Eq. (5)}$$

where

1 refers to top layer, 2 refers to base layer, B refers to back surface

and

$A(\lambda)$ = Absorptance at each wavelength interval, %

$R(\lambda)$ = Reflectance at each wavelength interval, $= R(\lambda)SC(\lambda)$, %

$T(\lambda)$ = Transmittance at each wavelength interval, %

λ = Wavelength of radiation, microns

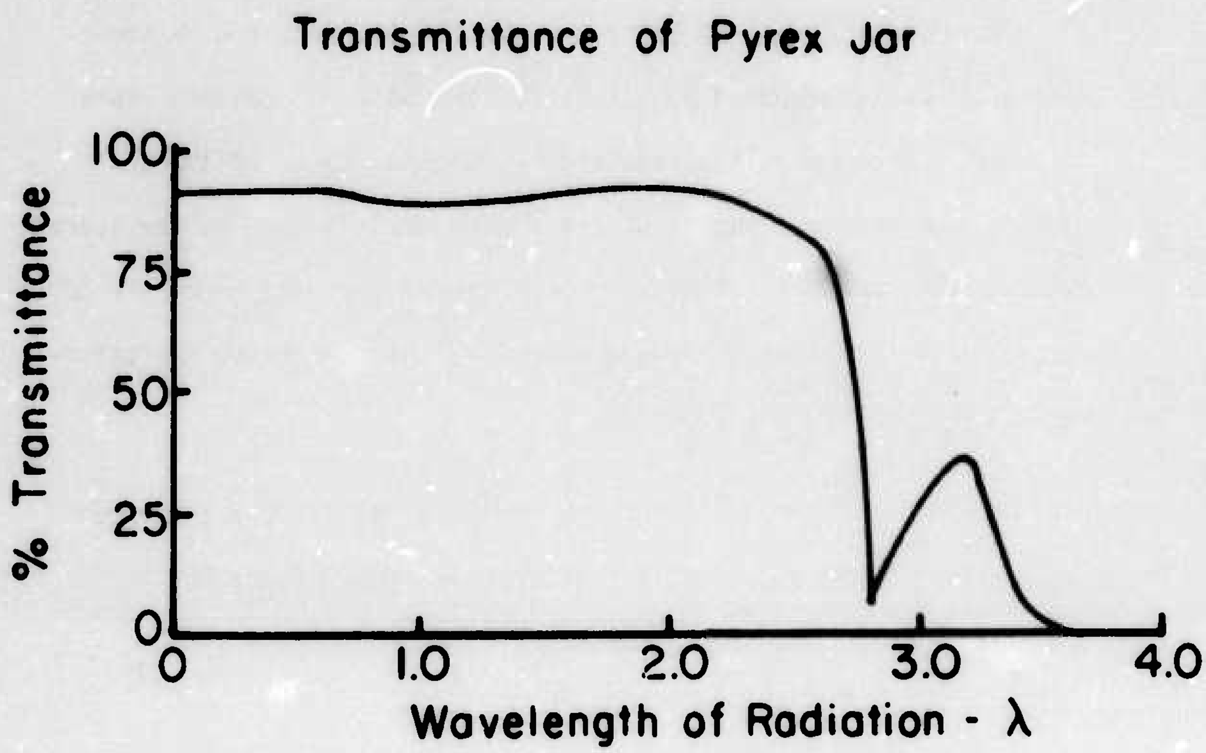


Fig. 2. Transmittance of Pyrex Bel' Jar

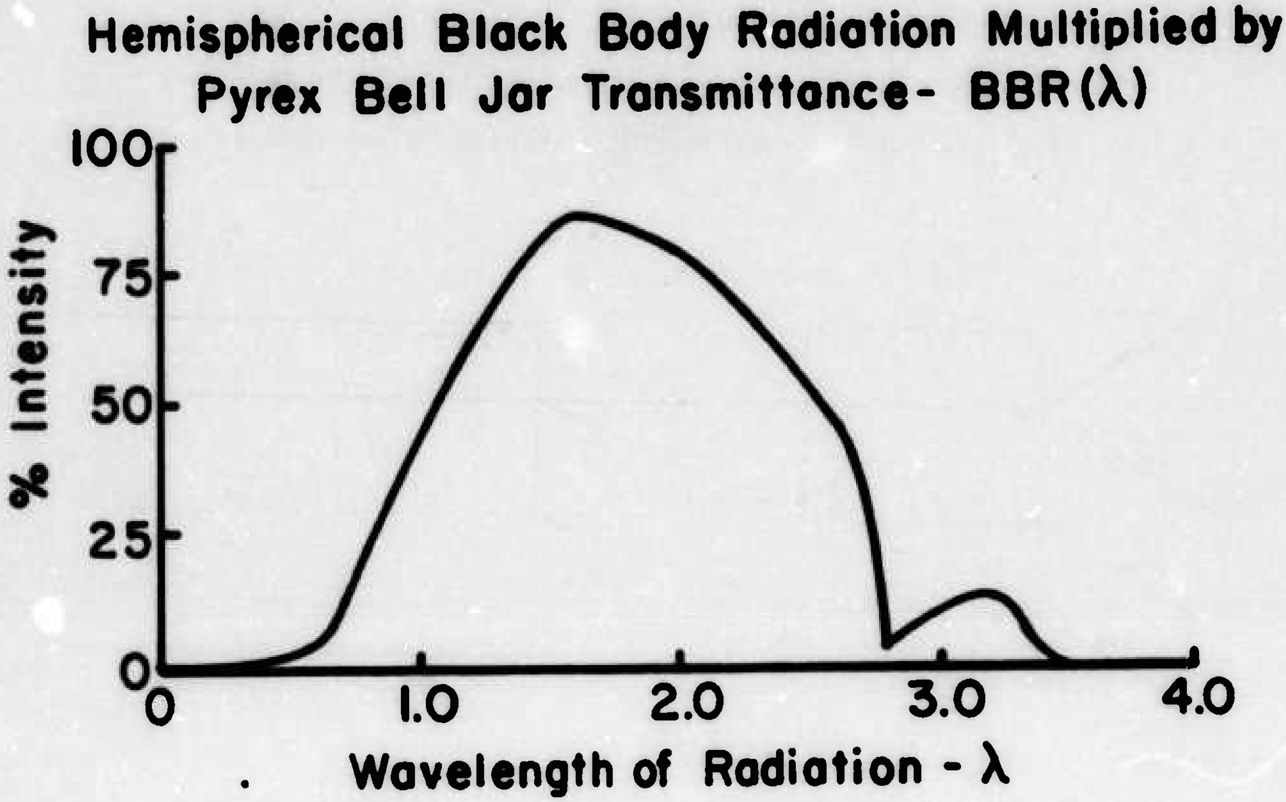


Fig. 3. Black Body Radiation Distribution

H = Heat flux perpendicular to surface, cal/cm^2sec

Q = Incident energy measured with a radiometer, cal/cm^2sec

BBR(λ)= Black Body Radiation at each wavelength interval, %

$$BBR_{(AV)} = \frac{1}{N} \sum_{\lambda = 0.375}^{\lambda = 3.825} BBR(\lambda)$$

N = Number of wavelengths of λ

Figure 4 shows the energy Q as it passes through the two-layer system. The interface is separated only to exhibit the optical paths of Q.

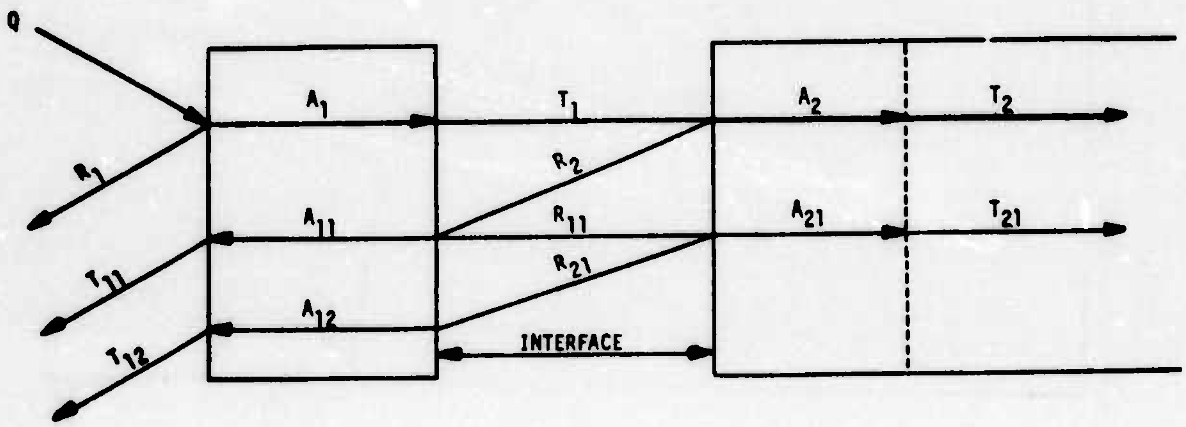


Fig. 4. Optical Paths of Energy through Two-Layer System

Referring to Figure 4, it is evident that Q measured by the radiometer is equal to the total energy incident, or:

$$Q = H1 + H1B + H2 + \frac{Q}{BBR_{(AV)}N} \sum_{\lambda = 0.375}^{\lambda = 3.825} BBR(\lambda)[R_1(\lambda) + T_1(\lambda) R_2(\lambda) T_{11}(\lambda) + T_1(\lambda) R_2(\lambda) R_{11}(\lambda) R_{21}(\lambda) T_{12}(\lambda)$$
$$+ T_1(\lambda) T_2(\lambda) + T_1(\lambda) R_2(\lambda) R_{11}(\lambda) T_{21}(\lambda)]$$

where for all wavelengths:

$$R_1(\lambda) = R_{11}(\lambda)$$

$$A_1(\lambda) = A_{11}(\lambda) = A_{12}(\lambda)$$

$$T_1(\lambda) = T_{11}(\lambda) = T_{12}(\lambda)$$

$$R_2(\lambda) = R_{21}(\lambda)$$

$$A_2(\lambda) = A_{21}(\lambda)$$

$$T_2(\lambda) = T_{21}(\lambda)$$

Where the first subscript refers to the layer and the second subscript refers to the iteration of reflectance, transmittance or absorptance.

The values of H1, and H1B and H2 established in terms of the optical properties of the first and second layer and the energy output, color temperature and transmittance through pyrex of the source radiation are used in a Griffith and Horton equation which considers the thermal properties of the first and second layer. The equation for calculating temperature rise caused by H1, H1B and H2 follows:

$$U_2 = \frac{2H\lambda\sqrt{D_1}}{\gamma} \sum_{n=0}^{n=\infty} \left(-\frac{1}{\gamma}\right)^n \left\{ 2\sqrt{\frac{D_2 t}{\pi}}\, e^{-\left\{x-a\left\{1-\sqrt{D_2/D_1}\,(2n+1)\right\}\right\}^2/4D_2 t} - \left[x-a\left\{1-\sqrt{D_2/D_1}\,(2n+1)\right\}\right]\left(1-\operatorname{erf}\frac{x-a\left\{1-\sqrt{D_2/D_1}\,(2n+1)\right\}}{2\sqrt{D_2 t}}\right)\right\} \qquad \text{Eq. (6)}$$

where

subscript 1 refers to top layer 1, subscript 2 refers to base layer 2

and U = Temperature rise

H = Heat flux perpendicular to surface

X = Total thickness from surface to point of temperature rise measurement

a = Thickness of layer 1

D = Thermal diffusivity = k/S

k = Thermal conductivity

S = Volume specific heat (density x specific heat)

$$\gamma = \frac{k_2 S_2 + \sqrt{k_1 S_1 k_2 S_2}}{k_2 S_2 - \sqrt{k_1 S_1 k_2 S_2}}$$

$$\lambda = (k_2\sqrt{D_1} - k_1\sqrt{D_2})^{-1}$$

t = Time

Equation 6 is used to calculate the temperature rise caused by H1, H1B and H2. When calculating the temperature rise caused by:

H1, x equals 0.1032 cm and α equals 0.0532 cm,

H1B, x equals 0.050 cm and α equals 0.0532 cm, or

H2, x equals 0.050 cm and α equals 0.0 cm.

The total temperature rise at depth in the second layer is equal to the sum of the individual temperature rises:

$$U2 = U21 + U22 \qquad \text{Eq.(7)}$$

where

U2 = Total temperature rise at depth in layer 2

U21 = Temperature rise caused by H1

U22 = Temperature rise caused by H2 plus H1B

H1B is added to H2 because the levels of energy contributed by H1B were found to be small in our particular application.

The physical and thermal properties of the silicone rubber and the skin simulant are shown in Table I.

TABLE 1

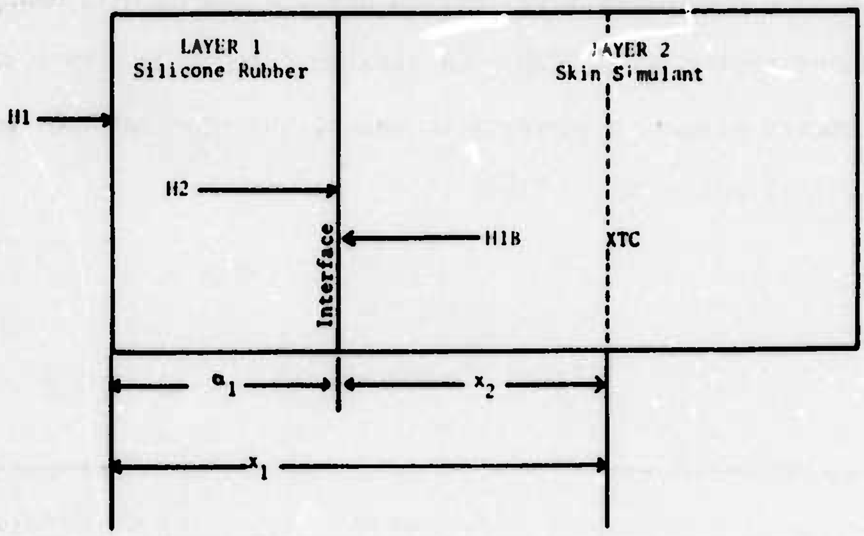
Physical And Thermal Properties of Silicone Rubber And Skin Simulant

Symbol	Property	Units	Silicone Rubber subscript 1	Skin Simulant subscript 2
RHO	Density	gm/cm^3	1.0968	1.8200
C	Specific Heat	cal/gm°C	0.3500	0.3571
K	Thermal Conductivity	cal/cm°C sec	5.00×10^{-4}	1.31×10^{-3}
S	Volume Specific Heat	cal/cm^3°C	0.3839	0.6499
D	Diffusivity	cm^2/sec	13.02×10^{-4}	20.16×10^{-4}
α	Thickness	cm	0.0532	1.0

The heat flow relationships of the silicone rubber patches and the skin simulant, and the corresponding values for x and α are indicated in Figure 5.

FIGURE 5

Heat Flow Relationships and Distances



x_1 = distance from surface where H1 is absorbed to TC = 0.1032 cm

a_1 = thickness of layer 1 = .0532 cm

x_2 = distance from surface where H2 is absorbed to TC = 0.050 cm

TC = site of thermocouple embedded 0.050 cm beneath surface of simulated skin

The instrumentation required follows:

A Honeywell Oscillograph Model 1508 with type M40-350 galvanometers is used to record experimental data. A Hy-Cal Engineering Model C-1301-A-15-072 Radiometer is used to measure the Heat Flux output of an Arthur D. Little, Inc. Model CSAF-3 Compound Radiation-Imaging System. The radiation system is capable of heating a square area 1/2 inch on a side with a flux of up to 15 cal/cm^2sec with a uniformity of $\pm$ 1%. It consists of a resistance heated graphite element used in conjunction with a compound thermal

imaging system and a heat flux-redistributor to provide the desired flux uniformity (2). The skin simulant has a fine copper-constantan thermocouple embedded .050 cm beneath its surface to measure the temperature at depth. The radiometer and the skin simulant thermocouple were calibrated using a Minneapolis Honeywell Potentiometer Model 2720. Calibrations are made with a voltage standard placed in series with each transducer and the system-sentitivities are shown in Table II.

TABLE II

System Sensitivities

	Radiometer	Skin Simulant
Transducer Sensitivity	0.4255 $cal/cm^2 sec/MV$	23.66°C/MV
System Sensitivity	0.01198 $cal/cm^2 sec/MM$	0.3697°C/MM

The protocol for conducting the experiment follows:

1) adjust radiation source to desired level of heat flux output.
2) take 4-second exposure using radiometer.
3) take 10-second exposure of one pigmented patch on skin simulant.
4) take 4-second exposure using radiometer.
5) allow 5-minute cooling period for skin simulant.
6) change to another pigmented patch.

7) repeat steps 2 through 6 until all pigmented patches are irradiated.

8) adjust radiation source to higher level of heat flux output.

9) repeat steps 2 through 8 until completion.

EXPERIMENTAL RESULTS

The experimental data is used to validate twc computer programs (Appendix A). Q, the incident energy measured with a radiometer, is entered into the H1H2 program. Table III is generated by the computer and gives values of H1 and H2 for each combination of pigmented patch and skin simulant for Q equal to 1.00 cal/cm^{2}sec.

TABLE III

Output From Computer Program H1H2

	W	W+1	W+2	W+3	W+4	W+5	BLACK
H1 =	.34970	.55450	.69526	.77211	.82475	.84806	.87556
H2 =	.25776	.16892	.10797	.07405	.04530	.03446	.02061

H1 and H2, the heat fluxes absorbed at the first and second layer, are entered into the DELT program and the computer generates the data in Table IV, i.e., time in seconds vs the temperature rise at depth in °C in the second layer caused by H1, H2 plus H1B and H1 plus H2 plus H1B for the W(white) patch on the skin simulant when

irradiated with a heat flux of 1.00 cal/cm^{2}sec. As observed in Table IV, a correction of -0.03 sec is applied to give an exact comparison with the experimental data at each recorded data point by compensating for the shutter opening time of 0.03 sec.

TABLE IV

Output From Computer Program DELT

H1 = .34970 H2 = .25776

TIME	DELTA T-H1	DELTA T-H2	TOTAL DELTA T
2.97	5.75	9.11	14.86
5.97	13.87	15.78	29.65
9.97	22.83	22.63	45.46

TIME	DELTA T-H1	DELTA T-H2	TOTAL DELTA T
.97	.56	2.96	3.52
1.97	2.90	6.30	9.20
2.97	5.75	9.11	14.86
3.97	8.59	11.56	20.16
4.97	11.31	13.77	25.07
5.97	13.87	15.78	29.65
6.97	16.29	17.65	33.94
7.97	18.58	19.40	37.98
8.97	20.75	21.06	41.81
9.97	22.83	22.63	45.46

Table V identifies the pigmented patch and the experimental and theoretical temperature rises per unit flux at 3 and 6 seconds. The column labelled "Experimental Δt/cal/cm^{2}sec corrected for Edge Effect" shows the influence of edge losses which is discussed in Stoll(6). At 6 seconds' exposure time a 4% edge effect must be made for the heat loss at the site of measurement because of the relatively small size of the radiation aperture. This edge effect correction increases with both time and intensity of heat

flux exposure.

TABLE V
COMPARISON OF EXPERIMENTAL AND THEORETICAL
TEMPERATURE RISE DURING IRRADIATION

Pigmented Patch	Experimental $\Delta t/cal/cm^2 sec$ @ 3 sec	Theoretical $\Delta t/cal/cm^2 sec$ @ 3 sec	Experimental $\Delta t/cal/cm^2 sec$ @ 6 sec corrected for edge effect	Theoretical $\Delta t/cal/cm^2 sec$ @ 6 sec
W	15.41	14.86	29.54	29.65
W + 1	15.40	15.08	31.96	32.33
W + 2	15.07	15.24	31.84	31.18
W + 3	15.32	15.31	32.47	35.15
W + 4	15.17	15.16	32.88	35.48
W + 5	15.11	15.16	32.83	35.74
BLACK	15.53	15.12	34.67	35.98

DISCUSSION AND CONCLUSION

The agreement achieved between the experimental and the theoretical results throughout the range of varied optical properties in the irradiated layers indicates that the method is reliable within experimental limits. The accuracy of the radiometer used for measuring the incident energy is $\pm$ 2.93% (7) and the accuracy of the galvanometer recording system is approximately 2%.

The fact that the experimental temperature rise is always lower than the theoretical at longer exposure times is ascribed to a systematic loss not accounted for in this method. Such a loss can occur through scattering or re-radiation from the surfaces. Much difficulty was encountered in measuring the reflectance of the

white silicone rubber patch. Also, we suspect that the thermal and optical properties of the patches change somewhat with increasing temperature. The value of the thermal conductivity constant of the silicone rubber was supplied by the manufacturer; individual measurements were not made for each silicone rubber patch and it is expected that each will vary somewhat from the value used in the equations. The overall level of accuracy, about 5%,is considered adequate for the application intended, namely, the measurement of the thermal conductivity in living human skin.

In conclusion, the validation of the two-layer system for describing transient heat flow was obtained by irradiating a series of increasingly dark, black-pigmented patches, overlaid on a skin simulant, comparing observed and theoretical temperature rise values. Energy was supplied by a graphite imaging furnace and temperature rise was measured at 0.05 cm beneath the surface of the skin simulant. Incident energy levels up to 1.0 cal/cm^{2}sec were used and close agreement was found between the experimental and theoretical results. Validation of the equations ensures that measurements of the temperature rise at the interface of the rubber patch and intact living skin may be used to determine the thermal conductivity of the skin. Furthermore, since the primary site of the skin burn injury is the epidermal-dermal interface, and all the pigment is contained in the epidermis, the system may also be adapted to evaluations of the effect of natural pigmentation by treating the skin itself as a two-layer system.

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APPENDIX A

Equation 1 - Absorptance at each wavelength interval in layer 1.

$$A1(\lambda) = 1 - [R1(\lambda) + T1(\lambda)]$$

Equation 2 - Absorptance at each wavelength interval in layer 2.

$$A2(\lambda) = 1 - [R2(\lambda) + T2(\lambda)]$$

Equation 3 - Heat Flux absorbed at the front surface of the first layer.

$$H1 = \frac{Q}{BBR_{(AV)}N} \sum_{\lambda = 0.375}^{\lambda = 3.825} BBR(\lambda)\, A1(\lambda)$$

Equation 4 - Heat Flux absorbed at the back surface of the first layer.

$$H1B = \frac{Q}{BBR_{(AV)}N} \sum_{\lambda = 0.375}^{\lambda = 3.825} BBR(\lambda)[T1(\lambda)R2(\lambda)A1(\lambda) + T1(\lambda)R2(\lambda)R1(\lambda)R2(\lambda)A1(\lambda)]$$

Equation 5 - Heat Flux absorbed at the front surface of the second layer.

$$H2 = \frac{Q}{BBR_{(AV)}N} \sum_{\lambda = 0.375}^{\lambda = 3.825} BBR(\lambda)[T1(\lambda)A2(\lambda) + T1(\lambda)R2(\lambda)R1(\lambda)A2(\lambda)]$$

where

1 refers to top layer, 2 refers to base layer, B refers to back surface.

and

$A(\lambda)$ = Absorptance at each wavelength interval, %

$R(\lambda)$ = Reflectance at each wavelength interval, = $R(\lambda)SC(\lambda)$, %

$T(\lambda)$ = Transmittance at each wavelength interval, %

λ = Wavelength of radiation, microns

$SC(\lambda)$ = Setting correction at each wavelength interval (5), %

H = heat flux perpendicular to surface, cal/cm^2sec

Q = Incident energy measured with a radiometer, cal/cm^2sec

BBR(λ) = Black Body Radiation at each wavelength interval, %

$$BBR_{(AV)} = \frac{1}{N} \sum_{\lambda = 0.375}^{\lambda = 3.825} BBR(\lambda)$$

N = Number of wavelengths of λ

Equation 6 - Temperature Rise at Depth in Layer 2.

$$U_2 = \frac{2H\lambda\sqrt{D_1}}{\gamma} \sum_{n=0}^{n=\infty} \left(-\frac{1}{\gamma}\right)^n \Bigg\{ 2\sqrt{\frac{D_2 t}{\pi}}\, e^{-\left\{x-a\left[1-\sqrt{D_2/D_1}\,(2n+1)\right]\right\}^2/4D_2 t}$$

$$-\left[x-a\left\{1-\sqrt{D_2/D_1}\,(2n+1)\right\}\right]\left(1-\operatorname{erf}\frac{x-a\left\{1-\sqrt{D_2/D_1}\,(2n+1)\right\}}{2\sqrt{D_2 t}}\right)\Bigg\}$$

where

subscript 1 refers to top layer 1, subscript 2 refers to base layer 2

and U = Temperature rise

H = Heat flux perpendicular to surface

X = Total thickness from surface to point of temperature rise measurement

a = Thickness of layer 1

D = Thermal diffusivity = k/S

k = Thermal conductivity

S = Volume specific heat (density x specific heat)

$\gamma = \dfrac{k_2 S_2 + \sqrt{k_1 S_1 k_2 S_2}}{k_2 S_2 - \sqrt{k_1 S_1 k_2 S_2}}$

$\lambda = (k_2\sqrt{D_1} - k_1\sqrt{D_2})^{-1}$

t = Time

$$\operatorname{erf}(Z) = 2/\sqrt{\pi} \int_0^Z e^{-y^2}\, dy$$

Total Temperature Rise at Depth in the Second Layer

$$U_2 = U_{21} + U_{22} \qquad \text{Eq.(7)}$$

where

U_2 = Total temperature rise at depth in layer 2

U_{21} = Temperature rise caused by H1

U_{22} = Temperature rise caused by H2 plus H1B

The programs are written for a Control Data Corporation 6600 Computer System using Fortran Extended language.

Computer Program to Calculate H1 and H1B plus H2:

```
      PROGRAM H1H2(INPUT,OUTPUT,TAPE1)
      DIMENSION BDR(70),SC(70),RQ(14,70),SSR(70),SST(70)
      DIMENSION H1(7,70),H1B(7,70),H2(7,70)
      DIMENSION TRUEH1(7),TRUH1B(7),TRUEH2(7)
      DIMENSION R(7,70),T(7,70),A(7,70),SSA(70),AQ(70)
      REWIND 1
      READ (1,3) (BDR(I),I=1,70)
      READ (1,3) (SC(I),I=1,70)
      READ (1,3) ((RQ(K,I),I=1,70),K=1,14)
      READ (1,3) (SSR(I),I=1,70)
      READ (1,3) (SST(I),I=1,70)
    1 FORMAT (1X,*Q=*)
    3 FORMAT (10(F5.4,1X))
    5 FORMAT (F15.0)
      PRINT 1
```

```
      READ 5,Q
      SUM=0.0
      DØ 7 I=1,70
      SUM=SUM+BBR(I)
    7 CØNTINUE
      B=SUM/70.0
      TØT=0.0
      D=B/Q
      DØ 9 I=1,70
      AQ(I)=BBR(I)/D
      TØT=TØT+AQ(I)
    9 CØNTINUE
      C=TØT/70.0
      PRINT 11,C
   11 FØRMAT(* Q=*,1X,F8.6,//)
      J=0
      DØ 15 K=1,13,2
      J=J+1
      DØ 13 I=1,70
```

```
      R(J,I)=RQ(K,I)*SC(I)
   13 CONTINUE
   15 CONTINUE
      J=0
      DO 19 K=2,14,2
      J=J+1
      DO 17 I=1,70
      T(J,I)=RQ(K,I)
   17 CONTINUE
   19 CONTINUE
      DO 27 J=1,7
      DO 25 I=1,70
      A(J,I)=1.0-(R(J,I)+T(J,I))
      IF(A(J,I))21,23,23
   21 A(J,I)=0.0
   23 CONTINUE
   25 CONTINUE
   27 CONTINUE
      DO 29 I=1,70
```

```
      SSA(I)=1.0-((SSR(I)*SC(I))+SST(I))
   29 CONTINUE
      DO 33 J=1,7
      DO 31 I=1,70
      H1(J,I)=(BBR(I)/D)*A(J,I)
      H1B(J,I)=((BBR(I)/D)*T(J,I)*SSR(I)*SC(I)*A(J,I))+
     1((BBR(I)/D)*T(J,I)*SSR(I)*SC(I)*R(J,I)*SSR(I)*SC(I)*
     2A(J,I))
      H2(J,I)=((BBR(I)/D)*T(J,I)*SSA(I))+((BBR(I)/D)*T(J,I)*
     1SSR(I)*SC(I)*R(J,I)*SSA(I))+((BBR(I)/D)*T(J,I)*SSR(I)*
     2SC(I)*R(J,I)*SSR(I)*SC(I)*R(J,I)*SSA(I))
   31 CONTINUE
   33 CONTINUE
      L=0
      DO 41 J=1,7
      SUMH1=0.0
      SUMH1B=0.0
      SUMH2=0.0
      L=L+1
```

```
      DØ 35 I=1,70
      SUMH1=SUMH1+H1(J,I)
   35 CØNTINUE
      TRUEH1(L)=SUMH1/70.0
      DØ 37 I=1,70
      SUMH1B=SUMH1B+H1B(J,I)
   37 CØNTINUE
      TRUH1B(L)=SUMH1B/70.0
      DØ 39 I=1,70
      SUMH2=SUMH2+H2(J,I)
   39 CØNTINUE
      TRUEH2(L)=(SUMH2/70.0)+TRUH1B(L)
   41 CØNTINUE
      PRINT 43
      PRINT 45,(TRUEH1(L),L=1,7)
      PRINT 49,(TRUEH2(L),L=1,7)
   43 FØRMAT(10X,*W*,7X,*W+1*,6X,*W+2*,6X,*W+3*,
     16X,*W+4*,6X,*W+5*,5X,*BLACK*)
   45 FØRMAT(* H1=*,7F9.5,/)
```

```
      49 FØRMAT(* H2=*,7F9.5,/)
         END
```

Output Generated by H1H2 Program:

Q= 1.000000

	W	W+1	W+2	W+3	W+4	W+5	BLACK
H1=	.34970	.55450	.69526	.77211	.82475	.84806	.87556
H2=	.25776	.16892	.10797	.07405	.04530	.03446	.02061

Computer Program to Calculate Temperature Rise at Depth in Layer 2:

```
         PRØGRAM DELT(INPUT,ØUTPUT)
         DIMENSION U2(100),U21(100),U22(100),TIME(100)
         REAL K1,K2,LAMBDA
         RHO1=1.0968
         RHO2=1.8200
         C1=0.3500
         C2=0.3571
         K1=5.00E-4
         K2=1.31E-3
```

```
      X1=0.1032
      ALPHA1=0.0532
      X2=0.05
      ALPHA3=0.00
    3 FØRMAT(F15.0)
    5 FØRMAT(2X,*H1=*)
    7 FØRMAT(2X,*H2=*)
      PRINT 5
      READ 3,H1
      PRINT 7
      READ 3,H2
      S1=RHO1*C1
      S2=RHO2*C2
      D1=K1/S1
      D2=K2/S2
      LAMBDA=1.0/(K2*SQRT(D1)-K1*SQRT(D2))
      GAMMA=(K2*S2+SQRT(K1*S1*K2*S2))/
     1(K2*S2-SQRT(K1*S1*K2*S2))
      C=-1.0/GAMMA
```

```
      MAX=10
      DØ 11 I=1,MAX
      TIME(I)=I-0.03
      SUM1=0.0
      N=-1
   33 CONTINUE
      N=N+1
      A1=(2.0*H1*LAMBDA*SQRT(D1))/GAMMA
      B1=2.0*SQRT(D2*TIME(I)/3.1415927)
      F1=(X1)-((ALPHA1)*(1.0-(SQRT(D2/D1)*((2.0*N)+1.0))))
      G1=-(F1**2)/(4.0*D2*TIME(I))
      E1=F1/(2.0*SQRT(D2*TIME(I)))
      P1=(Ø**N)*((B1*EXP(G1))-(F1*CØMERF(E1)))
      SUM1=SUM1+P1
      IF(N-5)33,33,35
   35 CØNTINUE
      U21(I)=A1*SUM1
   11 CØNTINUE
      DØ 19 I=1,MAX
```

```
      TIME(I)=I-0.03
      SUM2=0.0
      N=-1
   37 CØNTINUE
      N=N+1
      A2=(2.0*H2*LAMBDA*SQRT(D1))/GAMMA
      B2=2.0*SQRT(D2*TIME(I)/3.1415927)
      F2=(X2)-((ALPHA3)*(1.0-(SQRT(D2/D1)*((2*N)+1))))
      G2=-(F2**2)/(4.0*D2*TIME(I))
      E2=F2/(2.0*SQRT(D2*TIME(I)))
      P2=(Ø**N)*((B2*EXP(G2))-(F2*CØMERF(E2)))
      SUM2=SUM2+P2
      IF(N-5)37,37,39
   39 CØNTINUE
      U22(I)=A2*SUM2
   19 CØNTINUE
      DØ 21 I=1,MAX
      U2(I)=U21(I)+U22(I)
   21 CØNTINUE
```

```
      PRINT 23,H1,H2
   23 FØRMAT(2X,*H1=*,F8.5,2X,*H2=*,F8.5,/)
      PRINT 25
   25 FØRMAT(3X,*TIME*,11X,*DELTA T-H1*,8X,*DELTA T-H2*,6X,
     1*TØTAL DELTA T*,/)
      PRINT 27,TIME(3),U21(3),U22(3),U2(3)
      PRINT 27,TIME(6),U21(6),U22(6),U2(6)
      PRINT 27,TIME(10),U21(10),U22(10),U2(10)
   27 FØRMAT(2X,F5.2,12X,F6.2,12X,F6.2,12X,F6.2)
      PRINT 29
   29 FØRMAT(/)
      PRINT 25
      DØ 31 I=1,MAX
      PRINT 27,TIME(I),U21(I),U22(I),U2(I)
   31 CONTINUE
      PRINT 29
      END
      FUNCTIØN CØMERF (U)
C     APPRØXIMATIØN FØRMULA - CØMPLEMENTARY ERRØR FUNCTIØN
```

```
      CØMERF=1./(((((((.430638E-4*U+2.765672E-4)*U+1.520143E-4)
     1*U+92.705272E-4)*U+422.820123E-4)*U+705.230784E-4)*U+1.)*
     2*16.
      RETURN
      END
```

Output Generated By DELT Program:

W(White) Silicone Rubber Patch on Skin Simulant

H1= .34970 H2= .25776

TIME	DELTA T-H1	DELTA T-H2	TOTAL DELTA T
2.97	5.75	9.11	14.86
5.97	13.87	15.78	29.65
9.97	22.83	22.63	45.46

TIME	DELTA T-H1	DELTA T-H2	TOTAL DELTA T
.97	.56	2.96	3.52
1.97	2.90	6.30	9.20
2.97	5.75	9.11	14.86
3.97	8.59	11.56	20.16
4.97	11.31	13.77	25.07
5.97	13.87	15.78	29.65
6.97	16.29	17.65	33.94
7.97	18.58	19.40	37.98
8.97	20.75	21.06	41.81
9.97	22.83	22.63	45.46

W + 1 Silicone Rubber Patch on Skin Simulant

H1= .55450 H2= .16892

TIME	DELTA T-H1	DELTA T-H2	TØTAL DELTA T
2.97	9.11	5.97	15.08
5.97	21.99	10.34	32.33
9.97	36.20	14.83	51.03

TIME	DELTA T-H1	DELTA T-H2	TØTAL DELTA T
.97	.88	1.94	2.83
1.97	4.59	4.13	8.72
2.97	9.11	5.97	15.08
3.97	13.63	7.58	21.20
4.97	17.93	9.02	26.95
5.97	21.99	10.34	32.33
6.97	25.82	11.57	37.39
7.97	29.45	12.72	42.17
8.97	32.91	13.80	46.71
9.97	36.20	14.83	51.03

W + 2 Silicone Rubber Patch on Skin Simulant

H1= .69526 H2= .10797

TIME	DELTA T-H1	DELTA T-H2	TØTAL DELTA T
2.97	11.43	3.82	15.24
5.97	27.57	6.61	34.18
9.97	45.39	9.48	54.87

TIME	DELTA T-H1	DELTA T-H2	TØTAL DELTA T
.97	1.11	1.24	2.35
1.97	5.76	2.64	8.40
2.97	11.43	3.82	15.24
3.97	17.08	4.84	21.93
4.97	22.48	5.77	28.25
5.97	27.57	6.61	34.18
6.97	32.38	7.39	39.77
7.97	36.93	8.13	45.06
8.97	41.26	8.82	50.08
9.97	45.39	9.48	54.87

W + 3 Silicone Rubber Patch on Skin Simulant

H1= .77211 H2= .07405

TIME	DELTA T-H1	DELTA T-H2	TØTAL DELTA T
2.97	12.69	2.62	15.31
5.97	30.62	4.53	35.15
9.97	50.41	6.50	56.91

TIME	DELTA T-H1	DELTA T-H2	TØTAL DELTA T
.97	1.23	.85	2.08
1.97	6.39	1.81	8.21
2.97	12.69	2.62	15.31
3.97	18.97	3.32	22.29
4.97	24.96	3.95	28.92
5.97	30.62	4.53	35.15
6.97	35.96	5.07	41.03
7.97	41.01	5.57	46.59
8.97	45.82	6.05	51.87
9.97	50.41	6.50	56.91

W + 4 Silicone Rubber Patch on Skin Simulant

H1= .82475 H2= .04530

TIME	DELTA T-H1	DELTA T-H2	TØTAL DELTA T
2.97	13.56	1.60	15.16
5.97	32.71	2.77	35.48
9.97	53.84	3.98	57.82

TIME	DELTA T-H1	DELTA T-H2	TØTAL DELTA T
.97	1.32	.52	1.84
1.97	6.83	1.11	7.94
2.97	13.56	1.60	15.16
3.97	20.27	2.03	22.30
4.97	26.67	2.42	29.08
5.97	32.71	2.77	35.48
6.97	38.41	3.10	41.51
7.97	43.81	3.41	47.22
8.97	48.94	3.70	52.65
9.97	53.84	3.98	57.82

W + 5 Silicone Rubber Patch on Skin Simulant

H1= .84806 H2= .03446

TIME	DELTA T-H1	DELTA T-H2	TOTAL DELTA T
2.97	13.94	1.22	15.16
5.97	33.63	2.11	35.74
9.97	55.37	3.02	58.39

TIME	DELTA T-H1	DELTA T-H2	TOTAL DELTA T
.97	1.35	.40	1.75
1.97	7.02	.84	7.87
2.97	13.94	1.22	15.16
3.97	20.84	1.55	22.39
4.97	27.42	1.84	29.26
5.97	33.63	2.11	35.74
6.97	39.49	2.36	41.85
7.97	45.05	2.59	47.64
8.97	50.33	2.82	53.14
9.97	55.37	3.02	58.39

Black Silicone Rubber Patch on Skin Simulant

H1= .87556 H2= .02061

TIME	DELTA T-H1	DELTA T-H2	TOTAL DELTA T
2.97	14.39	.73	15.12
5.97	34.72	1.26	35.98
9.97	57.16	1.81	58.97

TIME	DELTA T-H1	DELTA T-H2	TOTAL DELTA T
.97	1.40	.24	1.63
1.97	7.25	.50	7.76
2.97	14.39	.73	15.12
3.97	21.52	.92	22.44
4.97	28.31	1.10	29.41
5.97	34.72	1.26	35.98
6.97	40.78	1.41	42.19
7.97	46.51	1.55	48.06
8.97	51.96	1.68	53.64
9.97	57.16	1.81	58.97

Data is presented in groups of 70 data points corresponding to 70 wavelenghts from 0.375 to 3.825 microns as illustrated below:

10=0.375,0.424,0.475,0.525,0.575,0.625,0.675,0.725,0.775;0.825

20=0.875,0.925,0.975,1.025,1.075,1.125,1.175,1.225,1.275,1.325,

30=1.375,1.425,1.475,1.525,1.575,1.625,1.675,1.725,1.775,1.825,

40=1.875,1.925,1.975,2.025,2.075,2.125,2.175,2.225,2.275,2.235,

50=2.375,2.425,2.475,2.525,2.575,2.625,2.675,2.725,2.775,2.825,

60=2.875,2.925,2.975,3.025,3.075,3.125,3.175,3.225,3.275,3.325,

70=3.375,3.425,3.475,3.525,3.575,3.625,3.675,3.725,3.775,3.825,

The Data File Key used in the H1H2 program follows. Each data point has a corresponding wavelength associated with it as described previously.

Data File Key

Lines 100 to 160 - Black Body Radiation Data - BBR(λ)

Lines 180 to 240 - Setting Correction Data - SC(λ)

Lines 260 to 320 - Reflectance of White Patch - R(λ)

Lines 330 to 390 - Transmittance of White Patch - T(λ)

Lines 400 to 460 - Reflectance of W + 1 Patch - R(λ)

Lines 470 to 530 - Transmittance of W + 1 Patch - T(λ)

Lines 540 to 600 - Reflectance of W + 2 Patch - R(λ)

Lines 610 to 670 - Transmittance of W + 2 Patch - T(λ)

Lines 680 to 740 - Reflectance of W + 3 Patch - R(λ)

Lines 750 to 810 - Transmittance of W + 3 Patch - T(λ)

Lines 820 to 880 - Reflectance of W + 4 Patch - R(λ)

Lines 890 to 950 - Transmittance of W + 4 Patch - T(λ)

Lines 960 to 1020 - Reflectance of W + 5 Patch - R(λ)

Lines 1030 to 1090 - Transmittance of W + 5 Patch - T(λ)

Lines 1100 to 1160 - Reflectance of Black Patch - R(λ)

Lines 1170 to 1230 - Transmittance of Black Patch - T(λ)

Lines 1250 to 1310 - Reflectance of Skin Simulant - SSR(λ)

Lines 1330 to 1390 - Transmittance of Skin Simulant - SST(λ)

TAPE 1

100=.0002,.0007,.0030,.0090,.0214,.0423,.0817,.1164,.1679,.2297,

110=.2944,.3620,.4302,.4834,.5243,.5645,.6089,.6515,.6942,.7372,

120=.7750,.8209,.8691,.8878,.8833,.8758,.8682,.8607,.8541,.8446,

130=.8380,.8368,.8227,.8062,.7837,.7511,.7216,.6982,.6883,.6664,

140=.6300,.5981,.5718,.5451,.5267,.4946,.4303,.0624,.0189,.0334,

150=.0523,.0761,.0884,.1079,.1194,.1298,.1423,.1467,.1397,.1186,

160=.0729,.0320,.0072,.0031,.0000,.0000,.0000,.0000,.0029,.0025,

170=*EOR

180=.9763,.9688,.9650,.9650,.9625,.9575,.9537,.9513,.9475,.9425,

190=.9400,.9400,.9372,.9318,.9277,.9252,.9228,.9202,.9185,.9175,

200=.9165,.9155,.9138,.9112,.9093,.9078,.9073,.9078,.9073,.9058,

210=.9020,.8960,.8920,.8900,.8863,.8807,.8762,.8727,.8690,.8650,

220=.8645,.8675,.8682,.8667,.8690,.8750,.8810,.8800,.8800,.8800,

230=.8800,.8800,.8800,.8800,.8800,.8800,.8800,.8800,.8800,.8800,

240=.8800,.8800,.8800,.8800,.8800,.8800,.8800,.8800,.8800,.8800,

250=*EØR

260=.9999,.9999,.8554,.8293,.7698,.7578,.7090,.6819,.6454,.6312,

270=.6210,.5887,.5701,.5265,.5078,.4742,.3811,.4235,.4203,.3861,

280=.2838,.2316,.2966,.2443,.2921,.2791,.1765,.0634,.1170,.1683,

290=.2106,.1664,.1438,.1401,.1516,.1398,.0626,.0000,.0000,.0000,

300=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

310=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

320=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

330=.2510,.3360,.3570,.3680,.3740,.3890,.4120,.4270,.4430,.4550,

340=.4640,.4770,.4910,.5090,.5260,.5280,.4690,.5490,.5600,.5670,

350=.5100,.5160,.5610,.5490,.5960,.6020,.4720,.4120,.5280,.6000,

360=.6460,.6610,.6520,.6680,.6830,.6600,.5680,.4290,.2400,.3190,

370=.3320,.3890,.3930,.0510,.0600,.0350,.0250,.0190,.0000,.0000,

380=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

390=.0000,.0000,.0000,.0080,.0160,.0850,.1400,.1400,.1500,.2130,

400=.2310,.2330,.2260,.2110,.2010,.1940,.1920,.1900,.1890,.1920,

410=.2080,.2460,.2890,.2950,.2710,.2380,.2030,.2080,.2120,.2280,

420=.2380,.2610,.2950,.2990,.3130,.3090,.2420,.2020,.2380,.2580,

430=.2640,.2560,.2400,.2330,.2280,.2090,.1690,.1190,.0710,.0810,

440=.0810,.0860,.0830,.0900,.0800,.0590,.0590,.0590,.0590,.0590,

450=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

460=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

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470=.0280,.0370,.0400,.0430,.0470,.0500,.0560,.0610,.0690,.0790,

480=.0980,.1310,.1780,.2010,.1900,.1720,.1520,.1690,.1830,.2110,

490=.2280,.2630,.3120,.3270,.3610,.3700,.3000,.2690,.3330,.3670,

500=.3880,.3960,.3930,.4000,.4090,.4000,.3530,.2770,.1520,.2080,

510=.2190,.2580,.2640,.3130,.3030,.2100,.2100,.0280,.0280,.0280,

520=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

530=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

540=.1530,.1510,.1470,.1370,.128Q,.1220,.1200,.1180,.1170,.1210,

550=.1360,.1700,.2120,.2170,.1920,.1630,.1400,.1390,.1420,.1600,

560=.1760,.2030,.2330,.2420,.2570,.2520,.2080,.1770,.1980,.2060,

570=.2080,.1990,.1860,.1790,.1720,.1590,.1370,.1010,.0680,.0760,

580=.0750,.0790,.0770,.0810,.0760,.0580,.0580,.0580,.0580,.0580,

590=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

600=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

610=.0040,.0060,.0080,.0080,.0100,.0100,.0120,.0140,.0180,.0210,

620=.0310,.0490,.0800,.0960,.0860,.0710,.0620,.0680,.0770,.0960,

630=.1150,.1480,.1860,.2040,.2320,.2390,.1980,.1780,.2190,.2400,

640=.2550,.2600,.2580,.2620,.2680,.2620,.2370,.1820,.1010,.1410,

650=.1480,.1740,.1810,.2180,.2100,.1440,.1440,.0090,.0090,.0090,
```

660=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

670=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

680=.1210,.1160,.1120,.1030,.0960,.0930,.0900,.0880,.0880,.0910,

690=.1020,.1350,.1710,.1760,.1510,.1230,.1070,.1040,.1090,.1230,

700=.1420,.1680,.1960,.2070,.2170,.2110,.1760,.1530,.1660,.1720,

710=.1720,.1640,.1540,.1480,.1420,.1310,.1120,.0880,.0630,.0710,

720=.0700,.0730,.0710,.0720,.0740,.0580,.0580,.0580,.0580,.0580,

730=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

740=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

750=.0000,.0000,.0000,.0000,.0000,.0000,.0020,.0040,.0060,.0090,

760=.0120,.0230,.0430,.0530,.0480,.0390,.0310,.0340,.0400,.0520,

770=.0680,.0920,.1220,.1400,.1610,.1680,.1390,.1250,.1530,.1690,

780=.1790,.1810,.1800,.1820,.1880,.1820,.1630,.1280,.0700,.0970,

790=.1030,.1230,.1280,.1550,.1490,.1010,.1010,.0000,.0000,.0000,

800=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

810=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

820=.1030,.1010,.0980,.0900,.0860,.0810,.0790,.0770,.0770,.0790,

830=.0890,.1180,.1490,.1540,.1380,.1100,.0970,.0940,.0980,.1110,

840=.1290,.1520,.1790,.1900,.1980,.1930,.1680,.1480,.1550,.1570,

850=.1550,.1490,.1410,.1340,.1280,.1200,.1060,.0880,.0670,.0700,

860=.0710,.0720,.0700,.0720,.0710,.0570,.0570,.0570,.0570,.0570,

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900=.0040,.0100,.0200,.0270,.0210,.0180,.0130,.0140,.0180,.0260,

910=.0370,.0530,.0740,.0880,.1020,.1070,.0890,.0810,.0990,.1080,

920=.1120,.1120,.1110,.1120,.1140,.1110,.1000,.0770,.0410,.0590,

930=.0620,.0750,.0790,.0980,.0930,.0620,.0620,.0000,.0000,.0000,

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950=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

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970=.0810,.1060,.1390,.1450,.1230,.1010,.0880,.0850,.0900,.1010,

980=.1190,.1430,.1680,.1800,.1860,.1820,.1580,.1430,.1480,.1470,

990=.1460,.1390,.1300,.1230,.1190,.1100,.0990,.0840,.0630,.0700,

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1170=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

1180=.0020,.0030,.0060,.0080,.0060,.0030,.0030,.0030,.0040,.0070,

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1280=.0870,.0550,.0320,.0280,.0280,.0260,.0230,.0220,.0210,.0220,

1290=.0210,.0190,.0180,.0180,.0180,.0190,.0190,.0180,.0180,.0180,

1300=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

1310=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

1320=*EØR

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1370=.2320,.2000,.1240,.1140,.1550,.1990,.1750,.1140,.1140,.1140,

1380=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

1390=.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,.0000,

1400=*EØR

1410=*EØF
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